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Detrital cosmogenic ^{21}Ne records decoupling of source to sink signals by sediment storage and recycling in Miocene to present rivers of the Great Plains

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ABSTRACT

The preservation of conglomerates far from mountainous sources are commonly interpreted in terms of tectonic or climatic forcing. To relate a depositional signal to changing conditions in source areas, the process and duration of sediment routing from source to sink need to be determined. For the first time, we quantify sediment transport histories using cosmogenic ^{21}Ne in quartzite pebbles from modern river gravels and Neogene conglomerates from the modern and ancient North Platte River of the Great Plains of Nebraska. We demonstrate that at ~400 km from the Rockies mountain front, the majority of pebbles must have been stored in older channel deposits for up to several millions of years before being recycled; this is enabled by very slow to zero basin subsidence rates. This implies that upstream tectonic or climatic controls on surface processes are decoupled from the downstream depositional record; a result supported by the similarities in cosmogenic ^{21}Ne between Miocene, Pliocene and modern river channel pebbles despite known changes in tectonic and climatic forcing.

INTRODUCTION

The stratigraphic record of fluvial conglomerates far from their source area has been used to interpret: 1) the timing of thrust activity (Wiltschko and Dorr, 1983), 2) reduction in subsidence rates of basins adjacent to mountain ranges (Burbank et al., 1988; Allen et al., 2013), and 3) climatically-forced increases in late Cenozoic global erosion rates (Peizhen et al., 2001). The key to interpreting conglomerate progradation is to understand how coarse river bedload generated in upland catchments is routed hundreds of kilometres from mountain fronts into alluvial plains. The simplest interpretation is that repeated bedload transport during seasonal bankful discharge is able to selectively transport pebbles and cobbles hundreds of kilometres downstream before they are buried due to regional basin subsidence (Heller and Paola, 1992). However, the storage of conglomerates in paleo-channel networks and their recycling during erosion by younger channels of the modern floodplain in slowly subsiding sedimentary basins (Bridge and Leeder, 1979) requires longer durations of sediment routing and the progressive decoupling of source to sink signals. Testing these mechanisms requires quantification of the history of sediment routing including the effects of storage and recycling, which, until now, has not been achievable.

Determining rates of landscape change has been revolutionised by the measurement of in-situ cosmogenic nuclides, in particular the measurement of catchment-averaged erosion rates using ^{10}Be in river sediment (Brown et al., 1995). Despite the importance of sediment storage in floodplains, there have been few attempts to use cosmogenic nuclides to quantify sediment transport and storage on the 10 kyr to Myr time scale. Wittmann et al. (2009) and Wittman and von Blanckenburg (2009) used

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cosmogenic ^{10}Be and $^{26}Al/^{10}Be$ ratios in bulk sand from Amazon tributaries that drain the cratonic shield to argue for minimal storage and recycling.

The stable cosmogenic nuclides ^{3}He (Margerison et al. 2005) and ^{21}Ne (Ma and Stuart, 2017) do not decay after production, and so their measured concentrations record (minimum) surface exposure times of several million years, or erosion rates of less than 0.05 m/Myr. In the case of detrital material, the cosmogenic ^{21}Ne in quartz-rich pebbles from rivers can be used to quantify the spatial distribution of sediment production across a catchment (e.g., Codilean et al. 2008). Such studies assume that nucleogenic ^{21}Ne generated over the lifetime of the rock and cosmogenic ^{21}Ne produced during transport and storage of the sediment are trivial.

Here we report cosmogenic Ne concentrations in quartzite pebbles from the North Platte River on the Great Plains of Nebraska in order to test for the influence of sediment storage and recycling versus first-generation bedload transport in the routing of far-traveled (~400 km) conglomerates. We show that the cosmogenic ^{21}Ne generated during transport and storage on the flood plain dominates the inventory in most pebbles. The bedload transport rates needed to generate the cosmogenic ^{21}Ne in modern and Neogene pebbles are orders of magnitude lower than modern calculated bedload transport rates requiring flood plain storage for up to several millions of years before being recycled into active channels.

THE GREAT PLAINS OF NEBRASKA

The Great Plains east of the Rocky Mountains are dissected by east-flowing rivers such as the North Platte River in Wyoming and Nebraska (Fig. 1). The stratigraphy of the Great Plains records a regional unconformity separating Cretaceous strata from 50 to 250 m of overlying Oligocene to present-day aeolian and fluvial sediment (Condon, 2005). The current high elevation of the western Great Plains (~1600 m) has been interpreted in terms of increasing surface elevation driven by tectonics (Leonard, 2002; Heller et al., 2003). Reconstructed channel gradients of Miocene and Pliocene North Platte paleo-channels has been used to suggest hundreds of meters of surface uplift of the proximal river systems between 6 and 4 Ma (Duller et al., 2012). Subsequent dissection of the Great Plains by modern rivers is also interpreted in terms of climatic changes (Wobus et al., 2010; Pelletier, 2009).

The Neogene sedimentary record of the river systems of the Great Plains records several episodes of incision and aggradation (Swinehart et al., 1985). The succession comprises the White River Group (late Eocene to Oligocene), the Arikaree Group (Oligocene to Miocene) and the Ogallala Group (18–6 Ma). The upper Ogallala Group contains the Duer Ranch beds at its base (12–10 Ma) which incise into the underlying successions, and largely comprise conglomeratic channel units. Above this, the Ash Hollow Formation (10–6 Ma) comprises east-west oriented gravel-rich channel bodies encompassed in floodplain siltstones (Fig. 1; Diffendal, 1982). Following aggradation of this fluvial system, subsequent incision and aggradation deposited the Broadwater Formation between 3.7 and 2.5 Ma (Swinehart et al., 1985). Subsequent incision has resulted in the formation of the ‘Rocky Flats’ terrace surface that was incised from 1 to 2 Ma (Riihimaki et al., 2006), resulting in the modern topography of the plains. The gravels from the Ash Hollow and Broadwater Formations as well as the modern river channel contain clasts derived from the Rocky Mountains including quartzite pebbles from the

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Medicine Bow Range (Stanley, 1976; Swinehart and Diffendal, 1987) which form > 10% of the populations.

SAMPLES AND ANALYSIS

Twenty-six, 1–6 cm pebbles of quartzite derived from the Medicine Bow mountains (MBq) were sampled from the modern river channel, and ten from both Pliocene and Miocene channel deposits of the Broadwater and Ash Hollow Formations respectively (Supplementary Table). Sample sites are ~400 km from the mountain front, and ~1050 km from the Medicine Bow Mountains along the river channel (Fig. 1). The Miocene and Pliocene pebbles were selected from channel gravel bodies where the samples were shielded from modern exposure to cosmic rays. Images of sample locations are in Figures DR1–DR3 in the GSA Data Repository[1].

The non-atmospheric Ne (Ne*) in detrital quartz is largely composed of nucleogenic Ne (Ne_{nuc}), generated over the lifetime of the rock, and cosmogenic Ne (Ne_{cos}) generated during bedrock exhumation (Ne_{cosE}) and transport and storage in the fluvial system (Ne_{cosTS}). In order to determine the Ne_{nuc} concentration, quartzite samples (n = 4) were collected from the Medicine Bow Mountains from a > 12 m deep roadcut. Quartz preparation and Ne isotope analysis at SUERC followed established procedures (Codilean et al. 2008). The CREU quartz standard (Vermeesch et al. 2015) was analyzed throughout all analytical periods as an internal check on procedures.

RESULTS

The shielded MBq samples from the source area have low concentrations of the inherited nucleogenic ^{21}Ne (0.22–0.77 × 10^7 atoms/g) and have Ne isotope compositions that plot on or near the air-spallation mixing line (Fig. DR5). These results indicate that we can account for the inherited non-cosmogenic $^{21}Ne_{nuc}$, and so identify thecosmogenic $^{21}Ne_{cos}$ generated in the quartzite lithology during sediment exhumation and transport. Detrital sands from streams on the exposed quartzites of the Medicine Bow Mountains have been used to calculate exhumation rates of bedrock based on ^{10}Be concentrations of 0.32×10^7 atoms $^{10}Be/g$ (Dethier et al., 2014); this represents the slowest mean exhumation rates of the southern Rocky Mountains of 9 mm/kyr (Dethier et al., 2014). Based on the $^{10}Be/^{21}Ne$ production rate ratio of Balco and Shuster (2009), this yields a $^{21}Ne_{cosE}$ concentration of 0.08×10^7 atoms/g. Using the upper limits for both $^{21}Ne_{nuc}$ and $^{21}Ne_{cosE}$, the quartzite pebbles have inherited a maximum of 0.85×10^7 atoms $^{21}Ne/g$ prior to downstream transport and possible storage.

The MBq pebbles from the modern North Platte River yield $^{21}Ne^*$ concentrations of $1.1–12.6 \times 10^7$ atoms/g (Fig. 2; Table DR1). All samples plot within one standard error of the air-spallation mixing, and have $^{21}Ne^*$ concentrations that are in excess of the upper limit of inherited ^{21}Ne. By subtracting the inherited ^{21}Ne we obtain $^{21}Ne_{cosTS}$ concentrations that range from 0.25 to 11.75×10^7 at/g (Fig. 2).

All the MBq pebbles from Upper Miocene and Pliocene paleochannel deposits yield $^{21}Ne_{cosTS}$ concentrations ranging from 0.25 to 32.0×10^7 atoms/g and $0.12–6.02 \times 10^7$ atoms/g respectively (Fig. 2). Although fewer Pliocene and Miocene pebbles were analyzed than from modern deposits, a similar proportion (70%–80%) have $^{21}Ne_{cosTS}$ concentrations that are at least twice the inherited ^{21}Ne contribution.

The modern and ancient river systems contain pebbles with a significant variation in $^{21}Ne_{cosTS}$ concentrations acquired during the ~1050 km of sediment transport from the Medicine Bow Mountains to the sampling site. The median value of $^{21}Ne_{cosTS}$ in all three stratigraphic levels lies within the 1st and 3rd quartiles of each population, and so are not considered statistically distinct (Fig. 2 and supplementary Figure DR7). For the first time, these results enable us to determine the duration of exposure at or near the surface, and hence consider processes of sediment routing from the Miocene, Pliocene and modern North Platte River.

STEADY BEDLOAD TRANSPORT VERSUS STORAGE AND RECYCLING

The $^{21}Ne_{cosTS}$ in the MBq pebbles records cosmic ray irradiation in the upper few meters of the surface during sediment transport from the low-order tributaries of the Medicine Bow Mountains into the main channel of the North Platte River and downstream to the sample site. We assess whether the measured $^{21}Ne_{cosTS}$ can be generated by steady bedload transport. For sediment transport during bank-full floods, the highest possible concentrations are generated by slow pebble transport down the channel when the pebble remains at the surface of a gravel bar following each short-lived transport event. We construct a rudimentary and conservative model that assumes pebbles are transported incrementally down the modern river channel, and at each step, it calculates the acquisition of $^{21}Ne_{cosTS}$ based on changing production rates as a function of a pebble's elevation (graphical output and details of model in Supplementary Figure DR8). Production rates are determined using the Lal/Stone scaling (Lal, 1991; Stone 2000). This scaling scheme uses atmospheric pressure to determine production rate so we follow Balco et al. (2008) and convert latitude and elevation data along the river profile to pressure based on NCEP2 climate reanalysis data (Compo et al., 2011). For each run, the average downstream transport rate is held constant, and pebbles are assumed to always rest at the surface allowing for maximum accumulation of $^{21}Ne_{cosTS}$; in reality,

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pebbles will be submerged beneath a depth of water, and be buried within bedforms during the majority of their transport history. There is no accounting for pebble abrasion which again would increase the required exposure duration for a given $^{21}Ne_{cosTS}$ concentration. The purpose of this scenario is to calculate the maximum possible $^{21}Ne_{cosTS}$ accumulation: additional complexity in terms of sediment burial and abrasion would reduce the amount of $^{21}Ne_{cosTS}$. Our conservative estimate implies minimum transport time, without burial or abrasion, to accumulate enough $^{21}Ne_{cosTS}$ to account for the measured concentrations.

The model indicates that the lowest $^{21}Ne_{cosTS}$ (0.25×10^7 atoms/g) measured in the modern pebbles requires a bedload transport rate of 23 m/yr, while the average concentration (2.9×10^7 atoms/g) requires an average rate of 1.9 m/yr implying >550 kyr transport duration. The highest measured $^{21}Ne_{cosTS}$ concentration equates to modeled bedload transport durations of >5 Myr (Fig. 2).

We approximate the long-term (>10^4 yrs) bedload transport rates for the 1050 km channel reach based on a volumetric flux approach that aims at minimising the sediment flux rate, and so maximising its chances of being comparable to modeled results above for bedload transport. Average long-term bedrock exhumation rates of 9–31 mm/kyr are recorded by ^{10}Be concentrations (Dethier et al. 2014). The upstream catchment area of the North Platte River from the mountain front at the town of Douglas is 47,336 km^2 based on the digital topography (Fig. 1). By multiplying this area by the lowest erosion rate for the region (9 mm/kyr), we obtain a conservative estimate of sediment yield from the catchment area of 4.3×10^5 m^3/yr. The bedload proportion can be approximated at between 1 and 10% (Turowski, et al., 2010). Again, taking the most conservative option of 1% gives a bedload flux of 4.3×10^4 m^3/yr. The mean cross-sectional area of the active bedload in the North Platte channel can be estimated from a channel width of ~100 m from remote imagery, and an active bedload depth of 1.5 m based on documented bedform height (Crowley, 1983). By dividing the volume of bedload flux by the mean cross sectional area we obtain a minimum estimate for the mean bedload transport rate of 284 m/yr, averaged over thousands of years. Such transport rates would generate $\ll 1 \times 10^5$ atoms $^{21}Ne_{cosTS}$/g based on the model described above. We conclude that, even assuming minimum bedload transport rates with maximum source area residence times, the model of steady bedload transport down an active North Platte River is unrealistic to explain the measured $^{21}Ne_{cosTS}$ in the quartzite pebbles of the modern river sediment. We are unable to directly model the Miocene and Pliocene channels, but it is believed that they took a more direct route across the Front Ranges from the Medicine Bow Mountains (Diffendal, 1982; Condon, 2005), and that their elevations were lower than they are today (e.g., Duller et al., 2012). Consequently, $^{21}Ne_{cosTS}$ would have been even less than that for the modern river.

Based on the model calculations, we propose that the high and variable $^{21}Ne_{cosTS}$ concentrations must record acquisition during storage in a floodplain setting on a 10^5-10^6 (and possibly 10^7) year timescale followed by reworking into active channels (Fig. 3). The proximity of Miocene and Pliocene paleo-channels that run sub-parallel to the modern North Platte River has been well documented (Diffendal, 1982; Condon, 2005). Tributaries of the North Platte throughout the Great Plains of Nebraska and Colorado drain and recycle sediment from these paleochannels (Fig. 1).

Our data indicate that all the sampled pebbles in the modern and ancient channels of the North Platte River must have experienced periods of storage, with some for a combined minimum of 5 Myr, followed by recycling back into active channels (Fig. 3). This process can only take place where long-term sediment accumulation rates are slow relative to lateral channel migration rates and production rates of cosmogenic nuclides. This provides a mechanism by which slow basin subsidence rates facilitate long-distance progradation of conglomerates into sedimentary basins (Burbank et al., 1988; Paola et al., 1992; Allen et al., 2013). We conclude that in the modern and Neogene of the Great Plains, recycling of gravels is a requirement for the progradation of far-traveled conglomerates (Fig. 3). However, changes in water and sediment discharge or changes in channel gradients since the Miocene are not reflected in these data (cf. Leonard, 2002; Heller et al., 2003; Pelletier, 2009; Wobus et al., 2010; Duller et al., 2012). We conclude that this is a function of the decoupling and mixing of the signals between source area forcing and depositional response in these settings.

CONCLUSIONS

The concentration of cosmogenic ^{21}Ne in quartzite pebbles can be used to assess fluvial sediment routing when inherited ^{21}Ne is constrained. In the Great Plains of Nebraska, pebbles of quartzite from the Medicine Bow Mountains of Wyoming provide a suitable target for understanding the sediment dynamics of the North Platte River and its Miocene and Pliocene equivalents. The $^{21}Ne_{cosTS}$ content of quartzite pebbles ~400 km from the mountain front is orders of magnitude higher than would be achieved by steady sediment transport down the river channel. All the sampled pebbles require storage in, and recycling from paleo-channels, with the highest concentrations in a pebble requiring an absolute minimum of 5 Myr of storage. There is no significant difference in the cosmogenic ^{21}Ne inventory recorded by Miocene, Pliocene and modern North Platte River deposits. The results indicate an important decoupling and mixing of the signals between source area forcing and depositional response in these settings. . This is the first time that cosmogenic isotopes have been used to quantify sediment routing processes in modern channels. The data from the Cenozoic deposits (although less statistically robust) suggest that similar inferences are possible from ancient river channels. Future studies that combine stable and radioactive cosmogenic nuclides (e.g., ^{10}Be and ^{26}Al) will enable the history of sediment burial and recycling of modern sediments to be better quantified.

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FIGURE CAPTIONS

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Figure 1. Geological map showing the location of the North Platte River in the context of the Mississippi river system (A) and in its geological context with sample locations (B). Note that the modern North Platte River cross-cuts the Miocene (purple dashed) and Pliocene (blue dashed) paleochannels from Condon (2005). The grey outline is the modern drainage divide for the North Platte River, shading outside the modern catchment is in a lighter tone (see key).

Figure 2. Cumulative frequency diagram of cosmogenic $^{21}Ne_{cosTS}$ concentrations generated during sediment transport and storage in modern, Pliocene and Miocene quartzite pebbles sourced from the Medicine Bow Mountains sampled from the North Platte River, Nebraska (Fig. 1). Top axis equates to modeled minimum transport durations for pebbles sourced in the Medicine Bow Mountains and transported to the sample site in the plains. The highest concentration measured in a Miocene pebble equates to significantly greater than 5 Myr from source to sink.

Figure 3. Cartoon illustrating the process of the recycling of pebbles during the progradation of conglomerates over alluvial plains. Red arrows illustrate the transfer of ^{21}Ne-rich pebbles from abandoned channel-fills into an active channel. Graph represents the production rate as a function of depth in the Plains. The total measured $^{21}Ne^*$ combines $^{21}Ne_{nuc}$, $^{21}Ne_{cosE}$ and $^{21}Ne_{cosTS}$.

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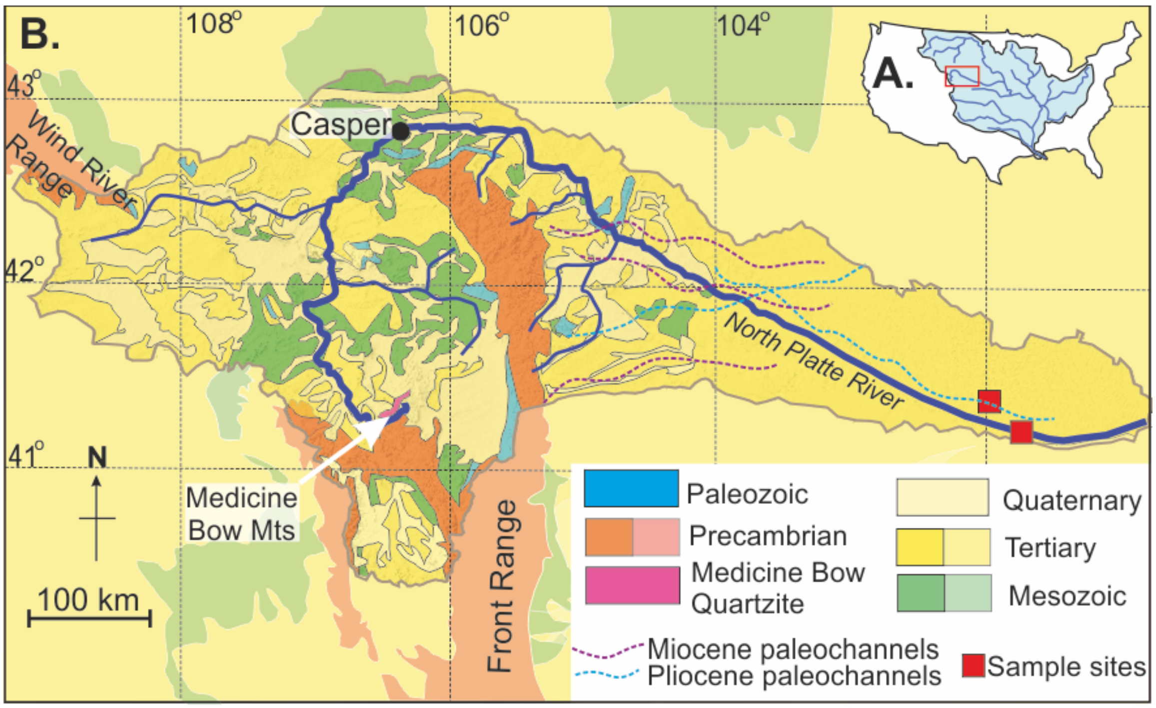

Figure 1. Geological map showing the location of the North Platte River in the context of the Mississippi river system (A) and in its geological context with sample locations (B). Note that the modern North Platte River cross-cuts the Miocene (purple dashed) and Pliocene (blue dashed) paleochannels from Condon (2005). The grey outline is the modern drainage divide for the North Platte River, shading outside the modern catchment is in a lighter tone (see key).

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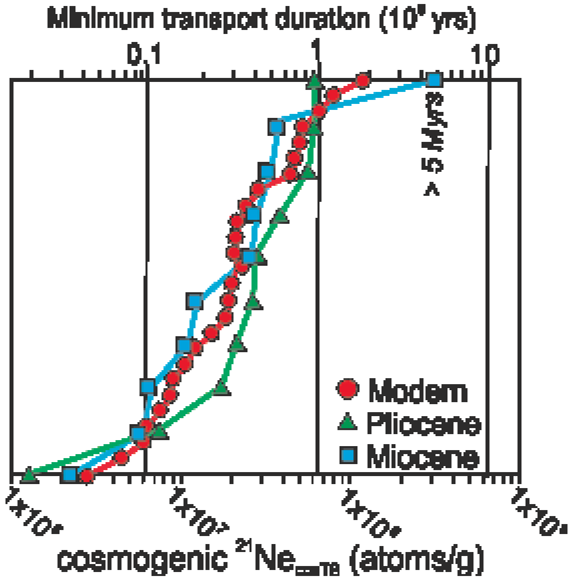
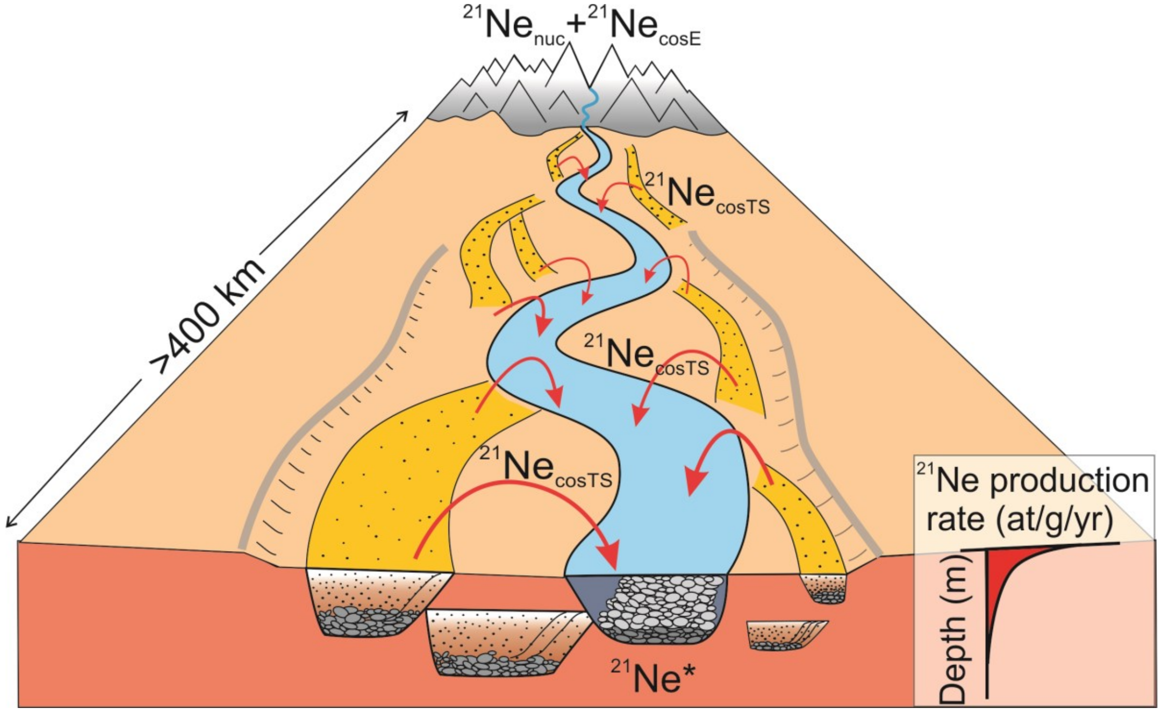


Figure 2. Cumulative frequency diagram of cosmogenic $^{21}Ne_{cosTS}$ concentrations generated during sediment transport and storage in modern, Pliocene and Miocene quartzite pebbles sourced from the Medicine Bow Mountains sampled from the North Platte River, Nebraska (Fig. 1). Top axis equates to modeled minimum transport durations for pebbles sourced in the Medicine Bow Mountains and transported to the sample site in the plains. The highest concentration measured in a Miocene pebble equates to significantly greater than 5 Myr from source to sink.

401 

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403 Figure 3. Cartoon illustrating the process of the recycling of pebbles during the

404 progradation of conglomerates over alluvial plains. Red arrows illustrate the transfer of

405 ^{21}Ne-rich pebbles from abandoned channel-fills into an active channel. Graph represents

406 the production rate as a function of depth in the Plains. The total measured ^{21}Ne*

407 combines $^{21}Ne_{nuc}$, $^{21}Ne_{cosE}$ and $^{21}Ne_{cosTS}$.

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